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A NOTE ON THE EFFECT OF HELICOPTER DYNAMICS ON STEEP INSTRUMENT APPROACHES

by

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FOREWORD

The research in this report was conducted by the Department of Aeronautical Engineering, Princeton University, under the sponsorship of the United States Army Transportation Research Command, Fort Eustis, Virginia, as Phase 4 of work under the ALART program.

The research was performed under the supervision of Professor Edward Seckel, Department of Aeronautical Engineering, Princeton University, and was administered for the United States Army by Mr. Robert Graham.

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SYMBOLS

$CP = \frac{\partial M}{\partial \delta}$	control sensitivity derivative $(\frac{\text{ft-lbs}}{\text{inch}})$
$\frac{CP}{I}$	control sensitivity parameter $(\frac{\text{rad/sec}^2}{\text{inch}})$
$D = \frac{\partial M}{\partial \dot{\Theta}}$	aircraft angular damping derivative $(\frac{\text{ft-lbs}}{\text{rad/sec}})$
$\frac{D}{I}$	angular damping parameter $(\frac{\text{ft-lbs}}{\text{rad/sec}} \times \frac{1}{\text{slug-ft}^2})$ or $(\frac{1}{\text{sec}})$
g	acceleration due to gravity $(32.2\ \frac{\text{ft}}{\text{sec}^2})$
I	appropriate axis moment of inertia (slug-ft^2)
M	pitch moment (ft-lbs)
$M_\alpha = \frac{\partial M}{\partial \alpha}$	angle of attack stability derivative $(\frac{\text{ft-lbs}}{\text{rad.}})$
$\frac{M_\alpha}{I}$	angle of attack stability parameter $(\frac{\text{ft-lbs}}{\text{rad.}} \times \frac{1}{\text{slug-ft}^2})$
$M_u = \frac{\partial M}{\partial u}$	longitudinal velocity stability derivative $(\frac{\text{ft-lbs}}{\text{ft/sec}})$
$\frac{M_u g}{I}$	velocity stability parameter $(\frac{\text{ft-lbs}}{\text{ft/sec}} \times \frac{\text{ft/sec}^2}{\text{slug-ft}^2})$
$M_q = \frac{\partial M}{\partial q}$	angular damping derivative $(\frac{\text{ft-lbs}}{\text{rad/sec}})$

$M_{\dot{\Theta}} = \frac{\partial M}{\partial \dot{\Theta}}$	angular damping derivative $\left(\frac{\text{ft-lbs}}{\text{rad/sec}}\right)$
α	angle of attack (radians)
u	longitudinal linear velocity (ft/sec)
Θ	pitch attitude (radians)
$\dot{\Theta} = q = \frac{d\Theta}{dt}$	pitch rate (rad/sec)

SUMMARY

A series of flight tests with a number of qualified pilots and a variable stability aircraft was conducted to determine the influence on pilot opinion of certain stability parameters in steep instrument approaches in turbulence with a helicopter. The parameters varied were: velocity stability - $M_u g/I$, angle of attack stability - M_α/I and angular damping - M_q/I or D/I.

Early in the flight tests it was determined that high values of angular damping were required in order to obtain acceptable approaches for the conditions of the test runs. The pilots readily noticed changes in angular damping and altered pilot opinion accordingly, whereas changes in the dynamics due to changes in the velocity stability or angle of attack stability were of much less concern and generally had an inconsistent influence on pilot opinion, even for relatively large increments of $M_u g/I$ and M_α/I. The pilots felt that the dynamics changes were "masked" by the strong angular damping, turbulence and the extremely difficult nature of the particular instrument approach tracking task, which required great concentration with frequent and rapid control action.

Also, all the problems associated with slow flight under instrument conditions in the presence of turbulence with "steep gradient" aircraft were evident to an increasing degree as glide slope angle was increased and flight speed decreased.

INTRODUCTION

Numerous investigations have been conducted on the feasibility of utilizing helicopters under all-weather instrument flight conditions. There is a desire to exploit the special flight capabilities of helicopters and future steep gradient aircraft. For example, it would be possible to reduce the airspace requirements for helicopters at high density terminal areas by special close-in steep approach paths because of the lower maneuvering speeds and the ability to execute steeper descents than conventional airplanes. From the military standpoint there is a natural desire to develop an all-weather capability in order to be able to accomplish routine instrument approaches to landings at heliports as well as at newly established front-line landing areas. Again the lower maneuvering speed and steep descent capability could be beneficial from the standpoint of the advantages gained by descents conducted in closer proximity to a protected landing site because of the close-in type approach. Also, additional benefits may be derived from the fact that problems associated with surrounding obstructions or terrain hindrances could be more easily avoided or virtually eliminated.

To realize these latent features of helicopters, studies have been made on IFR operational techniques, navigational aids, cockpit presentations or new pilot displays, approach systems and methods of improving helicopter characteristics for instrument flight. The object of this research was the determination of the influence of helicopter dynamics on pilot opinion and performance of steep descent instrument approaches in turbulence. A series of flight tests were conducted with a number of qualified pilots using a variable stability aircraft. The longitudinal dynamics were altered by changing the values of the velocity stability parameter $M_u g/I$, the angle of attack stability parameter M_α/I and the angular damping parameter D/I. A simulated ILS type approach system with varying beam widths and glide slope inclination angles was utilized. Pilot opinion data of selected configurations were obtained using the standard Cooper rating system and taped recordings of pilot commentary.

EXPERIMENTAL PROCEDURE

1. Description of Equipment

A variable stability HUP-1 tandem-rotor helicopter was used in the test program (Figure 3). Provisions were made for variation of pitch damping, velocity stability, angle of attack stability, and control power in the longitudinal mode. Lateral parameters were varied in a manner which would preserve harmony with the longitudinal characteristics. Changes in the stability derivative values were effected by sensing a flight variable and activating the longitudinal moment control in direct proportion to this signal. Rate gyros were used to sense aircraft angular rates, and a low inertia anemometer and vane mounted on a long boom were used to sense changes in aircraft velocity and angle of attack.

A cross-pointer type approach similar to ILS was provided by a simple tracking system. This consisted of a tracking theodolite and radio link to the standard ILS cross-pointer in the aircraft. Provisions were available for large variations in beam width and glide slope angle. The blue goggle/orange windshield method provided the evaluation pilot with an instrument flight environment.

In addition to the standard flight instruments and standard ILS angular position type indicator, use was made of a combined signal indicator (flight director) of the "zero reader" type (Figure 5). This type of combined signal indicator provides the pilot with a "quickened" presentation that might enable him to maintain a given flight path with less effort. By use of suitable quickening the pilot is aided in returning to an on-course flight following a positional error. The instrument effectively computes a best flight path for him to follow to correct a course error. Typical quickening consists of summing rates of departure or closure to the desired flight path and other

characteristic flight quantities, such as roll angle, with the radio angular position signal from the standard cross-pointer or ILS reference instrument.

In this research, the inputs to the vertical needle (azimuth or localizer) of the combined signal indicator were: angular positional error from the center line (radio angular positional signal), rate of departure or closure to center line (radio rate signal) and aircraft bank angle (in degrees of roll angle required for full scale deflection). The inputs to the horizontal or glide slope needle were: angular positional error above or below the glide slope (radio angular positional signal) and rate of departure or closure to glide path on-course (radio rate signal). The aircraft' s pitch and roll attitude was presented by the orientation of a ball behind the zero reader cross-pointers and a ball bank indicator was also mounted at the lower edge of this instrument.

Pitch attitude was not used as an input to the horizontal needle because as air speed decreases pitch attitude has a lesser influence on vertical rate. Glide slope corrections must be made by use of collective pitch and power. Current manuals on helicopter instrument flight techniques suggest that pitch attitude control is used primarily to maintain or change air speed (Reference 10).

Also,on the vertical needle, the localizer angular position signal was "backed off" with radio rate signal rather than direction information (compass heading). When using direction information of the compass such as runway heading for a canceling signal on the zero reader, care must be taken by the pilot to make allowances for "hang-off" or angular position error due to cross winds. Unless a combination of techniques are used, the aircraft will not fly down the correct center line even though the zero reader needle is centered. Also, the aircraft will not be aligned with the runway heading at the touchdown point when flying in a cross wind.

Both of these effects become more pronounced as cross wind velocity increases and flight speed decreases.

2. Artificial Turbulence Input

Test flights were conducted in calm air and artificial or canned disturbances were utilized to simulate atmospheric turbulence. These inputs operated the helicopter moment controls through the variable stability system and caused the random pitching, rolling, and yawing which simulated the turbulence. No pure translational gusts such as pure heave were simulated due to instrumentation limitations or the inability to affect pure translational forces with the helicopter control system.

The turbulence spectrum was obtained by passing "white noise" through a first order filter. This signal was mechanically recorded and used for inputs to all three axes. In addition to the individual roll and yaw noise inputs, two separate inputs were provided for the pitching disturbances. One input to the pitch axis represented a change in horizontal velocity due to a horizontal gust and the other represented a change in angle of attack due to a vertical gust. Assuming isotropic turbulence, both pitch inputs were identical in spectrum characteristics (frequency and amplitude) but the gain pot settings for each pitch turbulence input varied in proportion to the actual values of the velocity stability derivative and the angle of attack stability derivative being evaluated in each configuration. The value of the equivalent mean wind was 10 knots at 600 feet altitude. This level of disturbance was selected since current manuals on instrument flight techniques strongly suggest that instrument flight in a helicopter be conducted only if light to moderate turbulence conditions exist (Reference 10).

3. Flight Problem

The pilot's flight task consisted of maintaining level flight at 1200 feet absolute altitude at an azimuth angle of entry to the simulated ILS beam of approximately 45°. The tracking theodolite was operated during this

period, but the azimuth indication was full scale until the pilot intercepted the fringes of the beam. Also, the elevation indication was full scale "fly up" since at this phase the helicopter was below the glide slope beam. This is similar to standard ILS systems. After intercepting the azimuth beam, the pilot "flew" the flight director (zero reader) and attempted to center the vertical needle (azimuth indicator). If the pilot maintained centering of the zero reader, the helicopter would turn smoothly onto the correct beam azimuth and maintain beam azimuth for the remainder of the flight. The pilot continued to ignore the "fly up" presentation until the flight director or auxiliary ILS cross-pointer indicated interception of the elevation component of the beam. The point of initiating descent to follow the beam depended on the steepness of the beam. For very steep beams and high velocities it is necessary to anticipate or initiate descent before the glide slope presentation reads "on beam."

A total of approximately fifty approaches were made with this system.

4. Method of Obtaining Data

Three pilots were used to evaluate the test configurations. Two were experienced NASA test pilots with wide and diversified flying experience. The third was an Army pilot with similar flight experience. This pilot was instrument qualified and had some test pilot experience, but was not familiar with the zero reader type instrument. The qualifications of the pilots are shown in Table 2.

The familiar Cooper rating scale was used by the pilots to evaluate the various configurations. This scale is shown in Table 1. In addition to the pilot's rating of a configuration, a telemetered time history of the flight path error and other flight variables was available for analytic purposes.

In the analysis of the results of this particular investigation, considerable reliance was placed on the recorded conversations of the pilots both during flight and in post-flight conferences. For this particular type

of flying and task, pilot commentary was much more useful in determining the actual ratings and desirable flying qualities than the numerical Cooper rating system.

5. Range of Investigation

a. Aircraft

This investigation was primarily concerned with the longitudinal handling qualities. Thc lateral dynamics were adjusted to achieve a stable configuration in approximate harmony with the longitudinal characteristics.

The primary objective of this research program was the determination of the influence of the angle of attack stability and velocity stability on the flying qualities in the steep descent approaches. Several values of pitch damping were utilized. The values of the various parameters for the basic HUP in level flight at 35 knots were obtained from References 3 and 4 and are as follows: $M_u g/I$ (velocity stability parameter) equals -0.17 (minus sign is unstable), M_α/I (angle of attack stability parameter) equals +1.5 (plus sign is unstable), M_q/I or D/I (pitch damping parameter) equals -2.0 (minus sign denotes favorable damping), and CP/I (control power parameter) equals -0.5. Although the magnitudes of many of these parameters are known for the HUP in level flight at 35 knots airspeed, their actual values during the steep descents at 35 knots are not known. Only the incremental values for the range covered in this program are known with any degree of engineering certainty. For the investigations conducted during this research the maximum increment for each parameter was: $\Delta M_u g/I = +2.7$, $\Delta M_\alpha/I = -4.7$, $\Delta D/I = -6$, and $\Delta CP/I = -0.5$. The control power parameter, CP/I, was held constant at the overall value of -0.85, which was the value determined to be near optimum for the HUP-1 at 35 knots with D/I equal to an overall value of -6. The value of the pitch damping parameter, D/I, remained at an overall value of -6, although some flights (most of which were adjudged unsuccessful or unacceptable

test runs by the evaluation pilots because of low damping) were attempted at a relatively lower value of D/1 equal to -2.0 (basic HUP).

b. Approach System

A glide path elevation angle of 12° was used for the majority of the flight tests. Assuming a maximum rate of descent of 700 feet per minute as a practical limit for IFR operations (Reference 5), Figure 1 shows that an aircraft would be required to fly at 33 knots ground speed in order to maintain 700 feet per minute on a 12° glide slope. In order to obtain the more acceptable rate of descent of 500 feet per minute, the ground speed would be less than 25 knots. If 1200 feet absolute altitude (above the landing area) is assumed as the initial instrument approach altitude, the horizontal distance from the point of initiating the glide slope descent to the landing area is approximately 0.9 nautical miles for a 12° glide slope (Figure 2), as compared to approximately 4 nautical miles for present day airplane ILS systems with 2-1/2° to 3° glide slope inclination angles. A 12° approach angle would provide a fairly "close in" IFR letdown procedure at an airport. At some large airports a properly located landing pad would permit letdowns within the airport boundaries.

Beam widths ranged from ±6.7° to ±3.3° (full scale deflection either side) for the localizer course, and ± 3.0° to ±1.5° for the glide slope course. These, of course, are considerably wider beams than those used on the present-day airplane ILS approach systems. Normal ILS course widths are ± 2.0° to ±2.5° for localizer full scale and approximately ±0.5° glide slope full scale, (airplane ILS glide slope beam widths are really 0.5° full scale down and 0.3° full scale up, Reference 9). Several flights of an exploratory nature were conducted to investigate the effect of variations in the amount of quickening presentation on pilot opinion (ratio of respective inputs such as rate of deviation from beam to angular position from beam center line).

DISCUSSION

The general problem of steep descent instrument approaches to landings with steep gradient aircraft has been studied for the past several years (References 1,2,5,7, and 8). Previous investigations covered the problems encountered during slow speed precision flight in steep approaches and the effects of winds, turbulence, and weather minimums. Although there had been some early impression that helicopter type aircraft would naturally make letdown approaches vertically or near vertically under instrument conditions, it has been determined that the task rapidly increased in difficulty as glide slope angles increased and flight speed decreased. An understanding of the relationship between glide slope angle, ground speed, vertical rate of descent, and horizontal distance from the landing area may be obtained from Figures 1 and 2. In Figure 1 a plot of vertical rate of descent versus ground speed for various glide slope angles is shown. If it is assumed that 700 feet per minute is the <u>maximum</u> acceptable vertical rate of descent commensurate with satisfactory control and transition to visual flight for hovering or landing, the choice of steep glide slope angles becomes considerably limited unless very slow ground speeds are utilized. In a case of zero wind conditions (ground speed equals airspeed), the <u>minimum</u> velocity of the variable stability aircraft was limited to approximately 35 to 40 knots airspeed because of the heavy vibrations caused by interference effects and flow patterns of the overlapping rotor system of the tandem-rotor HUP. From Figure 1 it can be seen that the steepest glide slope approach angle that may be obtained for 700 feet per minute rate of descent and 35 knots ground speed is on the order of 12°. Assuming initial approach altitudes of 1200 feet above the landing area, the horizontal distance from the landing area is approximately 0.9 nautical miles for a 12° glide slope inclination angle (Figure 2).

By imposing the simple limitation (really a mandatory limitation from an operational point of view) on the maximum vertical rate of descent, the problems associated with IFR steep descent approaches in rotary wing aircraft become manifold and of major significance. Under these conditions, most of the problems normally encountered in slow speed flight are greatly compounded. As pointed out previously and especially in Reference 5, some of the problems confronting the helicopter pilot executing steep instrument approaches are:

1. The slope of the power required curve is the reverse of that for cruising so that control of altitude or glide slope can not be accomplished by pitch attitude changes, but must be done by changing power.

2. Small inadvertent deviations in lateral attitude or directional trim changes with power variation cause high turn rates and large heading errors.

3. With steeper glide slopes, the variation of rate of descent to correct for horizontal wind gusts increases. This imposes a very definite limit on the maximum approach angle practicable under gusty conditions.

4. At high descent angles the effects of wind gradients in both direction and velocity with height are appreciable in affecting control of the glide path. Frequently the wind velocity is on the order of the flight velocity.

5. At high rates of descent, the pilot could not safely observe reasonable weather minima and for this reason operational limits would permit maximum rates of descent on the order of 500-700 feet per minute.

6. If high rates of descent are permitted, the difficulty of initially establishing the desired glide path increases and the time for bracketing and correcting errors becomes shorter.

7. As glide slope angle increases, flight speed must decrease in order to maintain acceptable vertical rates of descent under instrument approach conditions.

8. At the lower airspeeds, aerodynamic behavior and control of the helicopter becomes poorer and the possibility exists of entering the vortex-ring state at moderate rates of descent with the additional difficulties of control.

9. At low speeds, very little normal accelerations or "g's" result from pitch attitude changes so that these normally useful cues are missing. These cues provide the pilot with another information path making him aware of the state or response of the system.

10. Extremely high instrument scanning rate is required of the pilot with present instrumentation.

11. Completely suitable speed indicators, (airspeed and ground speed), properly integrated flight instrumentation and a suitable approach navigation system are not presently available.

12. Intense concentration and a high degree of proficiency are demanded of the pilot in order to fly precision steep approaches in helicopters.

13. Also for helicopters with limiting "dead-man" zones and engine failure considerations, many of the steeper slow speed descent angles can not be used from the safety standpoint.

Although the above list of difficulties seems to imply an extremely difficult or unacceptable task, experiments have shown that certain vehicles with modified characteristics and displays are able to execute steep approaches satisfactorily for a certain range of parameters and conditions (References 1, 5, and 7). These configurations and approach conditions are considerably different from those used in general practice for current day standard airplane approach procedures.

The primary objective of this research program was the determination of the influence of the stability parameters $M_u g/I$ (velocity stability), M_α/I (angle of attack stability), and D/I (angular damping) on ILS type steep descent instrument approaches in helicopters.

a. Effect of Damping Parameter D/I

The effect of angular damping (D/I) on pilot opinion is already well known (References 6 and 7). Given enough control power (CP/I), pilot opinion of handling qualities always improves (for a rather large range of values) as angular damping is increased. In these experiments the pitch damping parameter was varied from the basic value of the HUP (D/I = -2) to three times the basic value (D/I = -6). It was evident that the pilots quickly detected changes in flying qualities due to changes in dynamics caused by angular damping changes and always desired the higher values. In fact, the opinion was generally offered that these steep instrument approaches required so much effort and concentration that strong angular damping had to be provided on all three axes in order to make the approach task tolerable. The pilots were inclined to give an unacceptable rating to the configuration and degrade the quality of the instrument approach in general unless the aircraft had strong angular damping. It appears that pilots request the strong angular damping because they quickly recognize that it tends to reduce the amplitude or severity of the motions of the vehicle due to turbulence. Also, the increased damping, given enough control power, provides the pilot with a suitable time constant for response to control. Favorable values of steady-state pitch rate are dependent on the ratio of control power to damping CP/D (Reference 6).

b. Effect of Stability Parameters $M_u g/I$ and M_α/I

The parameter $M_u g/I$ is the well known velocity stability parameter and M_α/I is the angle of attack stability parameter. The sign conventions used in this report are: velocity stability parameter is stable when positive and angle of attack stability parameter is stable when negative. The basic values of the two stability parameters for the 35 knot level flight condition for the HUP were:

$$M_u g/I = -0.17$$

$$M_\alpha/I = +1.4$$

The increments were:

$$\Delta M_u g/I = +2.7 \ (\approx 15 \text{ times basic level flight value})$$

$$\Delta M_\alpha/I = -4.7 \ (\approx 3\text{-}1/2 \text{ times basic level flight value})$$

Although the basic values of the parameters were not known exactly for the case of 35 knot descending flight, it was felt that the incremental values of $M_u g/I$ and M_α/I were large enough to obtain test configurations having both stable and unstable combinations of these two parameters. The variations of these parameters caused corresponding changes in the aircraft dynamic characteristics. However, pilots may notice alterations in flying qualities, caused by variations in $M_u g/I$ and M_α/I by detecting changes in the aircraft's response due to gusts and control deflection for trim, as well as changes in aircraft dynamics (period and damping).

In a previous study (Reference 6), it was established that the gust response of the helicopter and the control gradient required to trim a speed change were primary factors influencing pilot opinion in hover and low speed flight. The effect of the velocity stability parameter on the hovering dynamics is well known and changes in period and damping can be quite large. However, changes in pilot opinion due to large changes in the period and damping of the oscillatory mode were not strongly evident for the normal or usual range of parameters of current day vehicles. It is presumed that extreme variations outside the usual range of parameters would cause detrimental opinions of the dynamics. However, in the presence of turbulence, large adverse values in these parameters also increase the violence of the gust response of the vehicles with resultant frequent and rapid control inputs so that the pilots may not be able to notice the shorter periods anyway.

Attempts were made in this research program to alter the two stability parameters over a rather large range of values that included both stable and unstable velocity and angle of attack derivatives in order to determine their influence on pilot opinion in steep descent, instrument approaches in turbulence.

In the evaluation of the flight test runs, a number of interesting results were obtained when these two parameters were altered. The variations in the dynamics due to changes in the velocity stability parameter and angle of attack stability parameter were of little concern to the pilots and did not cause strong or consistent changes in pilots' opinion of handling qualities. This could be partially explained by the fact that the pilots stated that the extremely difficult nature of this particular task required so much concentration and varied procedures to control the flight path that repeated critical examinations of changes in period and damping were almost impossible. The process of sorting out changes in opinion solely due to changes in $M_u g/I$ and M_α/I for the ranges covered in this report frequently became a very confusing process for the pilot.

An analysis of the post-flight conversations seemed to confirm that the addition of strong angular damping combined with the difficult nature of the task tends to confuse the picture or at least "masks" the effects to the point where it is difficult for the evaluation pilot to detect any significant changes that alter pilot's opinion of the approach solely due to alterations in period and damping caused by variations in $M_u g/I$ and M_α/I. Alterations in the long period characteristics were not noticed because the pilots concentrated on the high frequency spectrum of the motions and did not allow the lower frequencies to develop. Frequent and rapid control action on the part of the pilot was required in order to perform the desired steering on the approach course. Therefore, the "tightness" of the pilot-control loop tended to conceal the lower frequency characteristics.

Also, for the conditions of these flight tests, significant or consistent changes in pilot opinion, due to changes in the gust response of the aircraft or stick trim gradient were not obtained for the range of increments of $M_u g/I$ and M_α/I. These results may be attributed to the fact that a relatively low level of turbulence was simulated and the control power sensitivity was optimized for the flight condition and angular damping.

Although most approach trials were made in calm air with the use of canned atmospheric turbulence, some approaches were also made in natural turbulence of varying intensity. All of the detrimental effects noted in Reference 5 were immediately evident with respect to wind shear, control of vertical rate of descent, stability, heading, air speed control, and steep glide slope angles.

c. Maximum Glide Slope Angle

Because of the limited time permitted for flight tests and the large number of quantities to be varied, no attempt was made in this phase to investigate a large variety of glide slope inclination angles. Also, because of the heavy vibration and poor aerodynamic behavior at slow speeds, the HUP was not suitable for speeds below approximately 35 knots in the steep descent approaches. As mentioned previously and according to Figure 1, the most favorable maximum approach angle for the HUP was 12° for the 35 knot case with vertical rate of descent limited to 700 feet per minute maximum.

d. Effect of Steady Winds

The effect of steady winds on the relationship between air speed and ground speed and the related influence on glide slope angle and vertical rate is shown in Figure 1. With steady head winds, the pilot is able to alter his approach conditions in a variety of favorable ways. Usually

the pilot increases his air speed (while still holding the approximate correct ground speed for the desired glide slope angle) or allows his vertical rate of descent to decrease. Since the HUP has poorer flight characteristics below 35 knots air speed, the pilots did not wish to maintain the proper ground speed by reducing their airspeed during approaches with tail winds. In order to stay on the glide slope at the higher ground speeds, the vertical rate was usually allowed to increase. On several runs with strong tail winds the pilots approached vertical rates that were close to auto-rotation for the HUP. Also, the anticipation of initiating a descent and the general problem of acquiring the glide slope accurately became more difficult at the higher ground speeds and steeper approach angles. The amount of time for bracketing and steering during the approach was shortened in relation to the strength of the tail winds. In general, pilots found steady tail winds objectionable and steady head winds favorable because of the above mentioned reasons.

e. Beam Widths

The beam widths for both the glide slope and localizer had to be considerably increased for helicopter steep descents. For the 12° inclination angle the pilots preferred a localizer beam width on the order of $\pm 7^{\circ}$ and a glide slope beam width on the order of $\pm 3^{\circ}$. These beam width values are approximately three and six times greater respectively than standard present-day ILS localizer and glide slope widths.

CONCLUSIONS

The following general conclusions are made for the range of parameters and test conditions studied in this report:

1. The well-known favorable effects of strong angular damping were again demonstrated. Given enough control power, pilot opinion improves as angular damping is increased. Strong angular damping was required in order to make the difficult approach task tolerable to the pilots and to obtain acceptable ratings of the configurations.

2. The relatively large incremental changes in the velocity stability parameter and the angle of attack stability parameter were of little concern to the pilots and did not cause significant or consistent changes in pilot opinion on the following effects and for the reasons listed:

   a. Dynamics changes - The pilots felt that the dynamics changes were "masked" by the strong angular damping and the extreme concentration required of the pilot just to perform the difficult instrument approach task. Alterations in the long period characteristics were not noticed because the pilots concentrated on the high frequency spectrum of the motions and did not allow the lower frequencies to develop. Frequent and rapid control action on the part of the pilot was required in order to perform the desired steering on the approach course.

   b. Response to gusts and stick trim gradient - Strong angular damping was utilized and a relatively low level of turbulence was simulated. The control sensitivity was optimized for the particular flight condition and angular damping.

3. Because of vibration limitations of the variable stability aircraft, the minimum operational airspeed in the steep descents was approximately 35 knots. Using this velocity and limiting the maximum rate of descent to 700 feet per minute, the steepest acceptable glide slope approach obtained was 12°.

4. For the 12° descent angle and the cross-pointer ILS type approach system, the localizer and glide slope beam width values had to be approximately three and six times greater respectively than those used on present day airplane ILS systems.

5. All the well-known detrimental effects associated with slow flight in turublence under instrument conditions were strongly and immediately evident in the steep descent approaches.

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Operating conditions	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only*	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition*	No	Doubtful
		8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

*Failure of a stability augmenter.

TABLE 1: Cooper Pilot Opinion Rating System

TABLE 2: Pilot Training and Experience Summary

Pilot A	graduate aeronautical engineer, NASA test pilot	
	wide flying experience, diversified flying time, 45 helicopter and V/STOL types, 160 airplane types, single and multi-engine, reciprocating and jet propelled.	
	total flight time	5000 hours
	total helicopter and V/STOL hours	1200 hours
	total fixed-wing hours	3800 hours
Pilot B	graduate aeronautical engineer, NASA test pilot	
	wide flying experience, diversified flying time, 20 helicopter and V/STOL types, 100 airplane types, single and multi-engine, reciprocating and jet propelled.	
	total flight time	7000 hours
	total helicopter and V/STOL hours	1000 hours
	total fixed-wing hours	6000 hours
Pilot C	U.S. Army test pilot - Edwards Experimental Flight Test Center	
	wide flying experience, diversified flying time, 6 helicopter types, numerous aircraft types.	
	total flight time	5000 hours
	total helicopter and V/STOL hours	3000 hours
	total fixed-wing hours	2000 hours

Rate of descent (ft./min.)

Ground speed (knots)

Figure 1: Relationship among Rate of Descent, Glide Slope Angle and Ground Speed

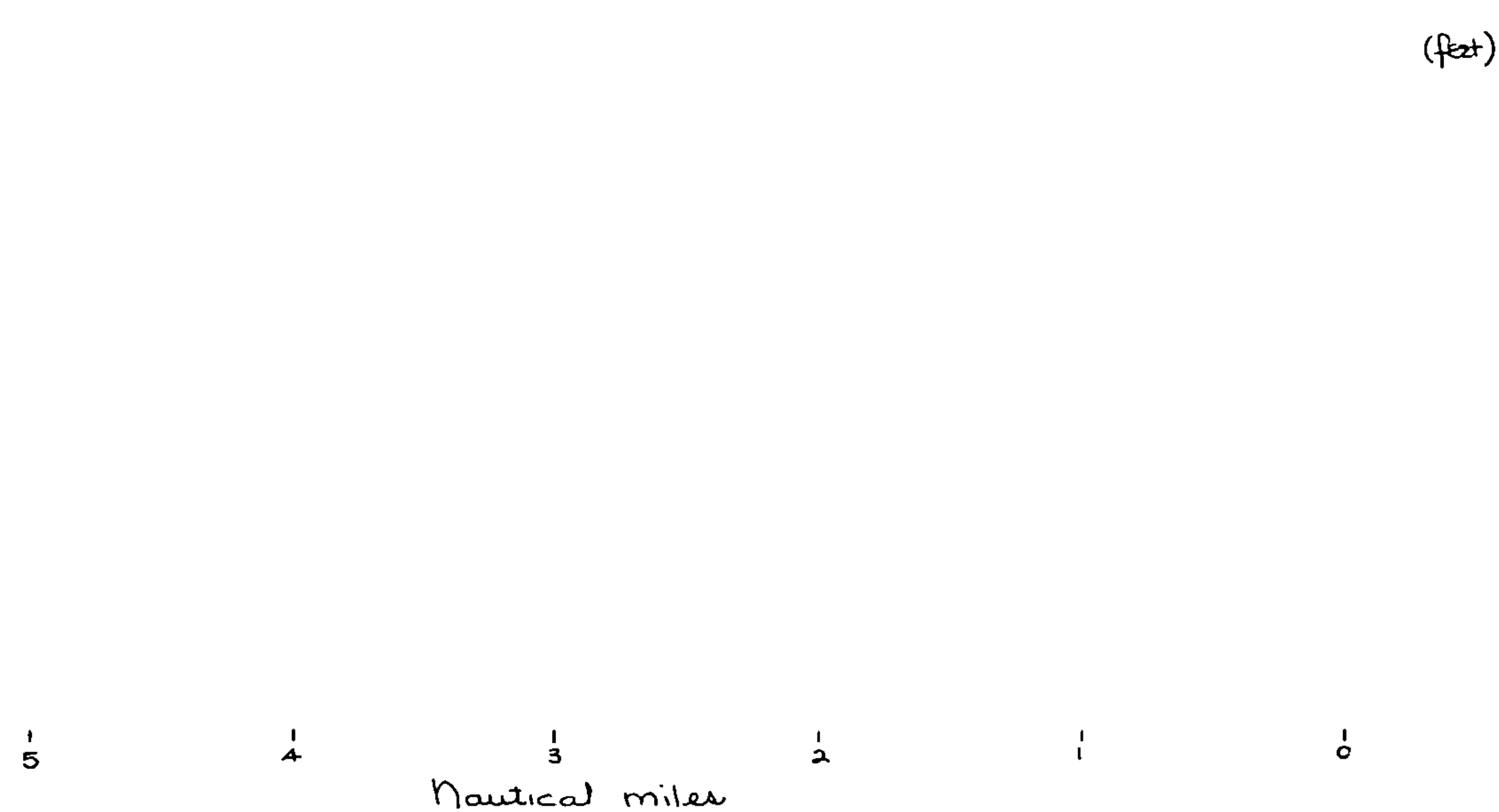

Figure 2: Glide Slope Angle vs. Horizontal Distance to Touchdown

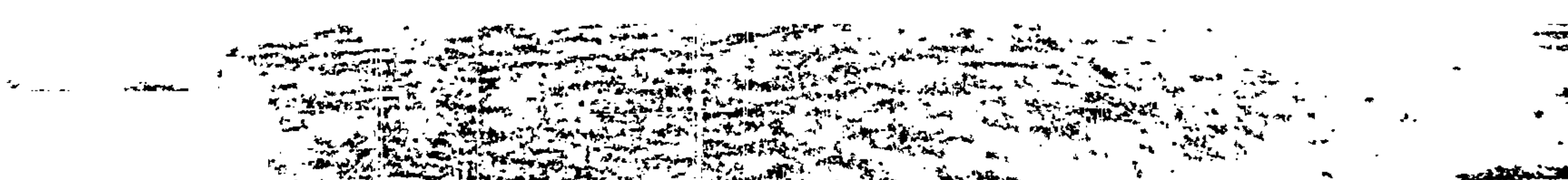

FIG. 3 VARIABLE STABILITY HELICOPTER

Figure 4 INSTRUMENT PANEL DISPLAY

NOTE:
ATTITUDE GYRO
INDICATES APPROX.
18° LEFT BANK
5° NOSE DOWN

ATTITUDE GYRO
WARNING FLAG (G)

FLIGHT DIRECTOR
WARNING FLAG (FD)

HORIZON
REFERENCE
LINE

ATTITUDE GYRO MINATURE
AIRCRAFT REFERENCE AND
ZERO READER STEERING
INDEX

ROLL TRIM
KNOB

BALL
INSTRUMENT

PITCH TRIM
KNOB

Figure 5 COMBINED SIGNAL INDICATOR

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Report No. 600, February 1962
25 pp. - illus. Unclassified Report
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